Why Do T Tauri Disks Accrete?

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ABSTRACT

Observations of T Tauri stars and young brown dwarfs suggest that the accretion rates of their disks scale strongly with the central stellar mass, approximately $\dot{M} \propto M_*^2$. No dependence of accretion rate on stellar mass is predicted by the simplest version of the layered disk model of Gammie (1996), in which non-thermal ionization of upper disk layers allows accretion to occur via the magnetorotational instability. We show that a minor modification of Gammie's model to include heating by irradiation from the central star yields a modest dependence of $\dot{M}$ upon the mass of the central star. A purely viscous disk model could provide a strong dependence of accretion rate on stellar mass if the initial disk radius (before much viscous evolution has occurred) has a strong dependence on stellar mass. However, it is far from clear that at least the most massive pre-main sequence disks can be totally magnetically activated by X-rays or cosmic rays. We suggest that a combination of effects are responsible for the observed dependence, with the lowest-mass stars having the lowest mass disks, which can be thoroughly magnetically active, while the higher-mass stars have higher mass disks which have layered accretion and relatively inactive or "dead" central zones at some radii. In such dead zones, we suggest that gravitational instabilities may play a role in allowing accretion to proceed. In this connection, we emphasize the uncertainty in disk masses derived from dust emission, and argue that T Tauri disk masses have been systematically underestimated by conventional analyses. Further study of accretion rates, especially in the lowest-mass stars, would help to clarify the mechanisms of accretion in T Tauri stars.

Subject headings: accretion disks - infrared: stars - stars: formation - stars: pre-main sequence

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1.   Introduction

The low-mass, pre-main sequence classical T Tauri stars (CTTS) are generally thought to be accreting mass from their circumstellar disks. Disk accretion through stellar magnetospheres provides a natural explanation of the ultraviolet and optical continuum excesses (e.g., Bertout, Basri, & Bouvier 1988; Königl 1991; Hartigan et al. 1990; Valenti, Basri, & Johns 1993; Calvet & Gullbring 1998) and the emission line profiles and strengths of many features (Edwards et al. 1994; Hartmann, Hewett, & Calvet 1994; Muzerolle et al. 2001).

Our understanding of accretion in ionized disks has been revolutionized by the rediscovery and application of the magnetorotational instability (MRI) to disk angular momentum transport (e.g., Balbus & Hawley 1998, and references therein). However, it was recognized some time ago that T Tauri disks are cold and thus likely to have such low ionization levels that the MRI cannot operate, at least in some (and quite possibly extended) regions of the disk, (e.g., Reyes-Ruiz & Stepinski 1995). This recognition lead Gammie (1996) to suggest that non-thermal ionization by cosmic rays could lead to accretion in upper disk layers, with a "dead zone" (a non-accreting, non-turbulent region) in the midplane. Further work suggested that X-rays from the central star could also provide a source of ionization (Glassgold, Najita, & Igea 1997), and these might even dominate if low-energy cosmic rays are excluded by turbulent magnetic fields in the outflows of T Tauri stars.

While it seems very likely that the very outermost layers of T Tauri disks are ionized, it is not at all clear that these ionized layers contain enough material to sustain observed T Tauri accretion rates; the column densities of MRI-active material can be quite small if dust grains do not settle and/or coagulate to an appreciable extent (e.g., Sano et al. 2000). Beyond this, as we discuss in the following sections, the standard layered accretion model has difficulties in explaining the dependence of mass accretion rates on stellar mass and age.

The other widely-recognized mechanism for transporting mass and angular momentum in disks that seems viable in pre-main sequence stars is gravitational instability (e.g., Tomley, Cassen, & Steiman-Cameron 1991; Laughlin & Bodenheimer 1994; Laughlin, Korchagin, & Adams 1998; see Gammie 2001, Johnson & Gammie 2003, and Durisen et al. 2006 for recent discussions). This is an especially attractive possibility in the earliest stages of stellar evolution, as it is quite likely that most of the mass of stars is accreted through the circumstellar disk, due to the finite (and large) angular momenta of protostellar clouds. On the other hand, T Tauri stars have clearly already accreted most of their mass, and typical disk mass estimates are an order of magnitude below the values required for gravitational instability (e.g., Beckwith et al. 1990; Andrews & Williams 2005). In addition, the surface densities required for gravitational instability appear to be implausibly large in the innermost disk; some other mechanism of transport must operate there.

In this paper we discuss the current evidence concerning T Tauri accretion rates and disk masses and their implications for the mechanisms of mass and angular momentum transport. We present a revision of the simple layered model of Gammie to include irradiation by the central star,

which introduces some dependence upon stellar mass through the dependence of disk heating on the stellar luminosity. The inclusion of irradiation does not appear to yield a sufficiently steep dependence of mass accretion rate on stellar mass to explain all the observations, although it might be consistent with the upper envelope of estimated accretion rates. A fully viscous disk might be able to explain the observations if the initial disk size is strongly correlated with the stellar mass, but it is not clear why disks around at least the most massive stars should be ionized down through to their midplanes at all radii. We suggest that the observed behavior of mass accretion in young stars may be a complicated mix of layered accretion with possible gravitational instability in the most massive stars and full viscous accretion in the lowest-mass objects.

2. The $\dot{M}$ - M_* relation

Observations spanning the range from 2-3 $M_\odot$ for intermediate-mass T Tauri stars to brown dwarfs (Calvet et al. 2004; Muzerolle et al. 2003a, 2005) suggest a strong dependence of mass accretion rate on stellar mass, roughly $\dot{M} \propto M_*^2$ (Figure 1). While observational selection effects tend to produce some correlation, because low accretion rates are not detectable in higher-luminosity stars, the overall trend of decreasing accretion rate with decreasing mass is clear (cf. Muzerolle et al. 2005). As shown in Figure 1, there is a large scatter in $\dot{M}$ at a given stellar mass M_* among populations of similar age, so that mass is not the only parameter controlling accretion.

One well-known mechanism which produces an M_*^2 dependence of the accretion rate on stellar mass is Bondi-Hoyle accretion:

$$\dot{M}_{BH} = \frac{4\pi G^2 \rho_\infty}{(c_\infty^2 + v_\infty^2)^{3/2}} M_*^2 \,, \tag{1}$$

where ρ_∞, c_∞ are the gas density and sound speed, and v_∞ is the velocity of the star of mass M_* relative to the ambient gas. Padoan et al. (2005) noted that the above relation provides the desired observed dependence of T Tauri accretion on stellar mass, and argued that the observed mass accretion rates could be explained quantitatively with realistic values of molecular cloud densities and velocity dispersions of stars and gas. Specifically, using moderately plausible values of $\rho_\infty = 2.46 \, m_H 10^3 \, \mathrm{cm}^{-3}$, $v_\infty = 1 \, km \, s^{-1}$, and $c_\infty = 0.2 \, km \, s^{-1}$, equation (1) yields an accretion rate $\dot{M} \approx 10^{-8} M_\odot \, \mathrm{yr}^{-1}$, consistent with observations of typical T Tauri stars (Hartmann et al. 1998), although Hartmann (2002) argued that many of the young stars in Taurus have velocities relative to their natal gas much smaller than $1 \, km \, s^{-1}$.

However, using the Bondi-Hoyle result implies that the angular momentum of the accreting gas is negligible, so that angular momentum transport in the accretion disk is unimportant. This assumption is highly questionable; if the angular momentum of the star-forming gas is indeed small, why do many T Tauri stars have such large disks ($\sim$ 100 AU or more, of order 10^4 stellar radii; e.g., Simon, Dutrey, & Guilloteau 2000)?

Moreover, in Sicilia-Aguilar et al. (2005) we showed that the mass accretion rates of the T

Tauri stars in the ~ 4 Myr-old young cluster Trumpler 37 are similar to those of Taurus young stars, even though Tr 37 resides not in a molecular cloud but within the expanding H II region IC 1396 (see discussion in Patel et al. 1995). Wendker & Baars (1980) developed an approximate model for this inhomogeneous ionized region, based largely on radio continuum observations at 2.7 GHz. They estimated an electron density (and thus a proton density) $N_e \sim 3.3\,\mathrm{cm}^{-3}$ in the central region where most of the cluster stars reside, although there are nearby denser regions with $N_e \sim 15\,\mathrm{cm}^{-3}$. Even if we take the larger of these values, the ambient gas density in Tr 37 is two orders of magnitude smaller than the typical value used by Padoan et al. for Taurus stars. Moreover, as the cluster resides within an H II region, the sound speed $\sim 10\,km\,s^{-1}$ must dominate the velocity term in equation (1); the denominator therefore is three orders of magnitude larger in the case of Tr 37 than for Taurus. This combination of density and velocity factors results in a predicted Bondi-Hoyle accretion rate five orders of magnitude lower than observed in Tr 37.

In summary, Bondi-Hoyle accretion is incapable of explaining the mass accretion rates in Tr 37, and is unattractive in general because of its great sensitivity to the properties of the environment. More broadly, this mechanism completely ignores the essential problem of angular momentum transport in disks, to which we now turn.

3. Layered MRI accretion

Gammie (1996) pointed out that cosmic rays (or other ionizing radiation such as X-rays; Glassgold et al. 1997; Gammie 1999) could produce a sufficient level of ions in "active layers" of surface density Σ_a that the magnetic field could couple effectively to the gas, allowing the MRI to operate. Assuming that the disk is heated primarily by viscous dissipation, Gammie derived an inner disk accretion rate $\dot{M}$ for a standard dust opacity law,

$$\dot{M} = 1.8 \times 10^{-8} \left(\frac{\alpha}{10^{-2}}\right)^2 \left(\frac{\Sigma_a}{100g\,cm^{-2}}\right)^3 M_\odot \,\mathrm{yr}^{-1}\,, \tag{2}$$

where α is the viscosity parameter and the fiducial active layer surface density is the estimated penetration depth of cosmic rays. Remarkably, this fiducial value of the mass accretion rate is of the same order as the accretion rates seen in typical T Tauri stars of near-solar mass (Gullbring et al. 1998; Hartmann et al. 1998; also Valenti et al. 1993). However, equation 2 exhibits no dependence upon stellar mass, which does not agree with the observations.

Equation 2 assumes that irradiation heating of the disk by the central star is not important. This may not be the case for the more massive, luminous stars, nor for the brown dwarfs, which have extremely low mass accretion rates and therefore presumably low viscous heating. The situation is mixed for solar-mass T Tauri stars, whose temperature structure in the innermost disk may or may not be dominated by viscous heating, depending upon the properties of the dust grains there (e.g., Figure 5a in D'Alessio et al. 2001). We therefore consider the limiting case in which the disk heating is set mainly by the absorption of radiation from the central star.

In Gammie's model, $\dot{M}$ decreases with decreasing radius. The mass accretion rate in the inner disk (and therefore the rate onto the central star) is set by the accretion rate of the layered model at the critical radius R_c where the temperature rises to a level (taken to be 1000 K) sufficient for thermal ionization to activate the MRI. In the model with pure viscous heating,

$$R_c = 0.13 \left(\frac{\alpha}{10^{-2}}\right)^{2/3} \left(\frac{\Sigma_a}{100g\,cm^{-2}}\right)^{4/3} \left(\frac{M_*}{M_\odot}\right)^{1/3} . \tag{3}$$

In the case where irradiation dominates, the temperature of the irradiated disk at cylindrical radius R will be

$$T^4 \sim \frac{L_*}{4\pi\sigma R^2}\gamma , \tag{4}$$

where γ is a geometrical factor accounting for the angle of entry of the stellar radiation into the disk. We consider two cases. First, we assume that the critical radius occurs essentially at the inner edge of the disk where the dust sublimates and thus the illumination is at near-normal incidence; this may be reasonable because the temperatures estimated at this point are $\sim 1400K$ (Muzerolle et al. 2003b), close to the temperature required for thermal activation of the MRI. A second case corresponds to the situation when the thermal activation temperature is achieved at radii exterior to the dust destruction radius but in the geometrically flat inner disk, in which case $\gamma \propto 1/R$.

For the first case, thermal activation at the dust destruction radius,

$$T_c \propto L_*^{1/4} R_c^{-1/2} \tag{5}$$

and therefore for fixed T_c

$$R_c \propto L_*^{1/2} . \tag{6}$$

Then for an "alpha" viscosity $\nu = \alpha c_s/\Omega$, where c_s is the central disk sound speed and Ω is the Keplerian angular velocity,

$$\dot{M} \propto \nu\Sigma \propto \alpha c_s^2 \Omega^{-1}\Sigma_a \tag{7}$$

$$\propto \alpha\Sigma_a L_*^{3/4} M_*^{-1/2} . \tag{8}$$

For pre-main sequence stars up to masses of $2M_\odot$ or so, the stellar luminosity tends to scale very roughly as $L_* \propto M_*^2$. Therefore in the limit of pure irradiation heating, we would expect

$$\dot{M} \propto \alpha\Sigma_a M_* . \tag{9}$$

If instead we assume that the critical temperature is achieved outside of the dust destruction radius but in the flat disk, then

$$R_c \propto L_*^{1/3} \tag{10}$$

which results in

$$\dot{M} \propto \alpha\Sigma_a M_*^{1/2} . \tag{11}$$

Thus, the inclusion of irradiation heating results in a layered model in which the accretion rate is no longer independent of stellar mass. While the predicted dependence is clearly not as steep

as the overall fit to the observations, it is intriguing that the first model of irradiation provides a dependence on mass not far from that of of the upper envelope of the accretion rates seen, as shown by the solid line in Figure 1, which indicates a relation $\dot{M} \propto M_*$. We return to this point later.

The detailed calculations of disk models by D'Alessio et al. (1999, 2001) suggest that irradiation heating does not necessarily dominate viscous heating in the inner disk, depending upon the mass accretion rate and dust opacity. This implies that the above results are limiting cases, and may overestimate the dependence of accretion rate on mass in the irradiated layered accretion model; more detailed models will be required to explore this further.

Equation (9) suggests that we look for an additional factor producing a dependence of either α or Σ_a on M_* to improve the layered model. If stellar X-rays rather than cosmic rays are responsible for ionizing the active layer (e.g., Glassgold et al. 1997; Igea & Glassgold 1999), the X-ray flux will depend upon the mass of the young star or brown dwarf, which in principle could produce a steeper dependence of $\dot{M}$ on M_*. From the recent study of stars in the core of the Orion Nebula Cluster, Preibisch et al. (2005) estimated that the ratio L_x/L_* is nearly the same for young brown dwarfs as for young low-mass pre-main sequence stars. However, the important factor is not the total luminosity but the X-ray flux at the critical radius where thermal ionization takes over. In the irradiation limit, the critical radius depends upon the flux of photospheric radiation. Since the fluxes of both photospheric and X-ray radiation should scale in the same way for the same geometry, there should be no effect. For example, even though a brown dwarf of mass $\sim 0.08 M_\odot$ has an X-ray luminosity $\sim 10^{-2}$ that of a typical $0.8 M_\odot$ T Tauri star, its R_c will be smaller by the factor $L_*^{1/2} \sim L_X^{1/2}$ in the first case and thus the *flux* $F_X(R_c) \propto L_X R_c^{-2}$ will remain constant. The same occurs in the second case of the flat disk, as the geometrical factors enter in the same way for both the X-rays and photospheric radiation.

Furthermore, the calculations of Glassgold et al. (1997) and Igea & Glassgold (1999) suggest that MRI ionization levels are maintained until the X-rays are very strongly attenuated; this makes the activated total column density depend very slowly on the X-ray luminosity. Thus variations in X-ray irradiation do not seem to produce a significant dependence upon stellar mass which would steepen the dependence of mass accretion rate on stellar mass in the layered model.

4. Viscous (pure MRI) disk evolution?

The layered model of Gammie (1996) implicitly assumes that the disk has high enough surface densities that it cannot be magnetically activated all the way to the midplane by cosmic or X-rays. If we examine equation (9) from an empirical perspective, the low accretion rates seen in brown dwarfs – roughly three orders of magnitude below typical T Tauri values – imply much lower disk surface densities in brown dwarf disks. This in turn suggests that such low-mass disks might be fully MRI-active. Indeed, Fromang, Terquem, & Balbus (2002) suggested that T Tauri disks in general might be able to sustain the MRI through their entire extent, even at reasonably high mass

accretion rates, if α is large enough and/or if a modest fraction of metal atoms are not locked into grains.

We can examine fully viscous disk evolution schematically by using the toy model introduced by Hartmann et al. (1998), assuming constant α and the disk temperature varies as $T \propto R^{-1/2}$. As shown in that paper, the disk mass M_d varies with time t as

$$M_d = \frac{M_d(0)}{(1 + t/t_v)^{1/2}} \,, \tag{12}$$

where $M_d(0)$ is the initial disk mass at time $t = 0$, and the initial viscous timescale is

$$t_v \propto \frac{R_1^2 \Omega}{\alpha c_s^2} \propto \frac{M_*^{1/2}}{\alpha T_1} R_1^{1/2} \,, \tag{13}$$

where R_1 is the initial (fiducial) disk radius at $t = 0$ and T_1 is the disk temperature at R_1. With $T_1 \propto L_*^{1/4} R_1^{-1/2}$ and $L_* \propto M_*^2$, this becomes

$$t_v \propto \frac{R_1}{\alpha} \,. \tag{14}$$

Differentiating equation (12) with respect to time to determine the mass accretion rate, and taking the limit of significant viscous evolution, i.e. $t \gg t_v$,

$$\dot{M} \propto \frac{M_d(0)}{t^{3/2}} \frac{R_1^{1/2}}{\alpha^{1/2}} \,. \tag{15}$$

It is plausible that the initial disk radius R_1 might have a dependence upon stellar mass. For example, suppose that the initial protostellar cloud can be approximated by either a singular isothermal sphere or a Bonnor-Ebert sphere (e.g., Alves, Lada, & Lada 2001). Then the protostellar cloud mass scales with its outer radius as $M_{out} \propto R_{out}$ for a fixed initial temperature, which we take as relatively constant. Then more massive stars will be formed from clouds with larger initial radii. This has implications for the size of the disk initially formed by the collapse of the protostellar cloud. Using the results of the uniformly-rotating isothermal sphere collapse calculations of Terebey, Shu, and Cassen (1984), the material from the outer edge of the cloud falls in to land on the disk at a radius

$$R_d \propto \frac{\Omega_\circ^2 R_{out}^4}{M_*} \,, \tag{16}$$

where $\Omega_\circ$ is the initial angular velocity of the cloud. Assuming that most of the mass rapidly is accreted into the central mass (see §7), i.e. that $M_{out} \sim M_*$, then $R_d \propto \Omega_\circ^2 M_*^3$. If we then identify $R_1 = R_d$ and take $\Omega_\circ = $ constant,

$$\dot{M} \propto t^{-3/2} \alpha^{-1/2} M_d(0) M_*^{3/2} \,, \tag{17}$$

or, assuming that the initial disk mass scales approximately with the stellar mass (see §7),

$$\dot{M} \propto t^{-3/2} \alpha^{-1/2} M_*^{5/2} \,. \tag{18}$$

This purely viscous result yields a strong dependence upon stellar mass, not too much larger than observed. (It may be more consistent with the lower envelope of the data points in Figure 1, but this is uncertain because of detection thresholds.) However, this solution is not without problems. For example, it is not clear that $\Omega_\circ$ should be independent of mass, or that its variation with mass would naturally produce a result even closer to M_*^2. More importantly, low mass accretion rates are accompanied by low disk masses in this model. Specifically, the disk mass at long times t scales at a given time as

$$M_d(t) = M_d(0)\frac{t_v^{1/2}}{t^{3/2}} \propto M_d(0) \left(\frac{R_1}{\alpha}\right)^{1/2} \propto M_d(0)M_*^{3/2} \,, \tag{19}$$

i.e. in the same way as the accretion rate. Thus the pure viscous solution requires that the brown dwarf disks with very low mass accretion rates have very low disk masses. While many brown dwarf disks have undetectable dust emission (so far), Klein et al. (2003) detected mm-wave emission from two young brown dwarfs, and Scholz, Jayawardhana, & Wood (2006) detected the 1.3mm emission from 5 of 19 Taurus brown dwarfs (one was previously detected by Klein et al.). The interpretation of these data is uncertain for reasons described more fully in §7, but the results suggest disk/star mass ratios of a few percent in these objects, similar to CTTS. It is not clear that *any* brown dwarf disks would be massive enough to be detected using the simple viscous scaling for low accretion rates.

It should also be pointed out that the above equations assume substantial viscous evolution in the disk, which only occurs if the initial disk radius R_1 is sufficiently small or if α is large. Collapse to initially large disks would result in very little overall viscous evolution and make the above analysis inapplicable. Some of the Hubble Space Telescope images of protostars in Taurus suggest infall to very large disk radii (Padgett et al. 1999) which would require very large values of α to result in substantial viscous evolution at typical T Tauri ages. In turn, large values of α needed for faster viscous evolution are problematic. Using the toy model of Hartmann et al. (1998) discussed above, the half-mass disk radius for an $\alpha = 10^{-1}$ would spread to nearly 1500 AU at an age of 1 Myr; and this may be a lower limit, because it assumes viscosity $\nu \propto R$ resulting from a disk temperature $T \propto R^{-1/2}$; cosmic ray heating will tend to drive the disk temperature to $T \sim$ constant, in which case the viscosity at large radii will be even higher and the disk expand even faster. While it is difficult to assign sizes to T Tauri disks because of the rapid decrease in surface brightness with radius, such large radii and rapid disk evolution seems implausible, especially given objects like TW Hya, which are still accreting at an age of 10 Myr (Muzerolle et al. 2000), for which the toy model would predict a truly enormous disk for $\alpha \gg 10^{-2}$, very much larger than currently detected.

5. The dust/metal problem

The surface density of the active layer in the inner disk is very sensitive to the presence of small dust particles, which can absorb ions and electrons in the gas. The estimates of Σ_a of Gammie

(1996) for cosmic rays and Glassgold et al. (1997) and Igea & Glassgold (1999) for stellar X-rays assumed substantial depletion of the small dust in the upper layers. While one expects settling and grain growth to occur naturally in T Tauri disks, it is not clear that the magnitude of these effects is quantitatively sufficient.

Sano et al. (2000) studied the effects of grain depletion and grain size on the surface density of the active layer for the case of a fixed cosmic ray ionizing flux, as in Gammie's original theory. For a standard interstellar medium grain size distribution, Sano et al. found that depletion factors of 10^{-4} were needed to produce $\Sigma_a \sim 10^2$ within 1 AU; a depletion of a factor of one hundred resulted in $\Sigma_a \sim 3\,\mathrm{g\,cm^{-2}}$ at 0.1 AU. Sano et al. also considered grain growth in the approximation that all the grains were one (large) size. For the case of no depletion, even grain growth to 1 μm resulted in very small $\Sigma_a \sim 1\,\mathrm{g\,cm^{-2}}$ at 0.1 AU.

Empirically estimating the amount of settling and grain growth is difficult from the current observations, but some rough limits can be set. D'Alessio et al. (1999) showed that, for a power-law distribution of grain sizes, maximum limits much greater than a few microns lead to washing out the 10μm silicate feature, in disagreement with observations. Combining the recent Spitzer IRS survey of Taurus disk spectra with disk models (Furlan et al. 2005; D'Alessio et al. 2006) suggests depletion factors of order 10^{-1} to 10^{-2}. These constraints are somewhat model dependent and uncertain, but it is difficult to explain the SEDs without a certain amount of disk "flaring" which can only be achieved if a significant amount of small dust still remains suspended in the upper layers. Thus there is no clear evidence that settling and/or grain growth in upper disk layers is large enough to provide much more than $\Sigma_a \sim 1 - 10\,\mathrm{g\,cm^{-2}}$ at 0.1 AU. Conversely, there is evidence for a substantial population of small grains in upper disk layers, based on the presence of silicate features (D'Alessio et al. 2001; Furlan et al. 2006) and the necessity of having enough short-wavelength opacity in the inner disk wall (at the dust destruction radius) to explain the magnitude of the near-infrared excess emission (e.g., Muzerolle et al. 2003b).

If dust growth and settling were an essential part of limiting the MRI, one might expect accretion rates to increase with age, whereas there is some evidence that the opposite occurs (Hartmann et al. 1998). Also, there is no evidence from the Taurus IRS survey that the disks with the least flaring indicated in their SEDs, which also tend to have the weakest silicate features suggesting grain growth, have larger mass accretion rates than those stars with less evidence for flaring and grain growth (Furlan et al. 2005, 2006). On the other hand, Fromang et al. (2002) took a more optimistic stance, suggesting that relatively small fractions of metal ions left out of grains could produce sufficient ionization. However, even in this case, Fromang et al. note that when $\alpha \leq 10^{-3}$ dead zones tend to appear no matter what the metal ion fraction becomes, simply because the X-rays do not penetrate through the entire disk at all radii.

In summary, fully viscous behavior at low disk and stellar masses seems possible and could be an explanation of very low accretion rates frequently seen in young brown dwarfs. The applicability of fully viscous evolution at larger stellar masses is far more uncertain.

6. Reynolds stress?

Fleming & Stone (2002) conducted numerical simulations of vertically-stratified disk models in which the upper layers were MRI-active while the central regions were quiescent. They found that, although the MRI did not operate in the magnetically dead zone, the turbulence in the upper layers could generate a significant Reynolds stress in the midplane, which would allow the dead layer to accrete albeit with a lower effective viscosity.

Fleming & Stone found that the Reynolds stress in the midplane never dropped below about 10% of the Maxwell stress in the active layers, and that there was significant mass mixing between active and dead layers. If this were generally the case for protostellar disks, it would simply mean that the effective α parameter for the evolution of the total surface density would simply be at most an order of magnitude lower in regions of dead zones. This would result in an increase in the mass surface density, which will be inversely proportional to α in steady state (e.g., Reyes-Ruiz & Stepinski 1995); it would yield a different dependence of mass accretion rate on disk parameters than in the original layered model, at large times being dependent on the mass supply from the outer disk as in the models of Hartmann et al. (1998); and it would limit the buildup of mass in the dead zone with time in the layered model, eventually evolving to a steady state.

However, for numerical reasons Fleming & Stone were able only to consider models in which the surface density of the active layer was of order 20% of the surface density of the dead layer or larger. An active layer of $\sim 100\mathrm{g\,cm^{-2}}$ could be 1% or less of the total surface density at 0.1 AU in a disk like that of the standard minimum mass solar nebula model. It seems intuitively unlikely that the turbulence generated in such an active layer could penetrate so effectively through such a relatively massive dead zone. The mass accretion rate depends upon the vertical integral of $\nu\Sigma$; if the viscosity in the dead zone drops by an order of magnitude, the Reynolds stresses will have to penetrate to a surface density larger by an order of magnitude or more in order to have any effect on $\dot{M}$. If the Reynolds stresses do not penetrate to very much deeper layers, they will not change the overall picture of layered accretion.

7. Gravitational instability?

The layered disk model is affected by many aspects of non-thermal ionization (e.g., grain growth and settling, X-ray fluxes, presence or absence of cosmic rays) whose effects could range from allowing a full MRI to operate to shutting it off completely at some radii except for very thin surface layers. The ubiquity of disk accretion among young stars (when inner disks are present) exhibiting a substantial but finite range of accretion rates at a given mass (Hartmann et al. 1998) suggests that some process might be operating which minimizes the possible variations in MRI activity.

One process of angular momentum transfer that plausibly operates during at least the pro-

tostellar phase is gravitational instability. The collapse of the protostellar cloud almost certainly results in most of the material initially landing at large disk radii, which is a strongly unstable condition. It seems highly plausible that the bulk of the protostellar material is thus driven inward towards the central regions by gravitational torques. This raises the question: why not view the T Tauri accretion process as the not-fully-completed end of the gravitationally-driven phase?

If gravitational instabilities are dominant in transferring most of the mass from the initial disk to the central star, the only way for the disk to be highly gravitationally stable at the end of the protostellar phase is if the MRI or some other mechanism is very efficient in driving accretion. While the MRI should be extremely efficient in the inner disk, where thermal ionization is high, and quite plausibly also in outer disk regions, where X-rays can penetrate and recombination rates are low, there might still be a dead zone at intermediate radii which might be driven into gravitational instability by continually accumulating material from the outer disk.

A major reason why gravitational instabilities have not been strongly advocated for T Tauri disks is that disk masses seem to be too low. Disk masses need to be of the order of 0.1 of the stellar mass for gravitational instabilities to operate (Pringle 1981), while typical T Tauri disk mass estimates have been of the order of 0.01 $M_\odot$, roughly a minimum-mass solar nebula. A very recent comprehensive survey of the Taurus star-forming region suggests a median disk mass of $5 \times 10^{-3} M_\odot$ (Andrews & Williams 2005), albeit with a large scatter. This median mass estimate is an order of magnitude lower than what is required for gravitational instability, though estimates for a small number of objects are much closer to the limiting value.

However, the uncertainty in disk masses estimated from dust emission is often not sufficiently recognized. Adoption of typical estimated long-wavelength opacities of interstellar dust results in implausibly large disk masses, and the spectral indices of observed mm- and sub-mm wave emission from T Tauri disks also suggest that the dust grains have evolved substantially in the disk (e.g., Beckwith & Sargent 1991; Andrews & Williams 2005, and references therein). D'Alessio et al. (2001) considered power-law distributions of dust sizes and showed that dust growth to maximum sizes greater than about 1 mm results in a spectral index determined by the power law of the size distribution, not the maximum size of the grains. If the maximum size is much larger than 1 mm (for the dust properties considered by D'Alessio et al. 2001), the mm-wave opacity can be much lower than assumed in typical observational estimates, while maintaining a fixed spectral index determined by the distribution of dust sizes. In the D'Alessio et al. calculations, only maximum dust sizes within a factor of 3 to 10 of 1 mm provide mm-wave opacities close to the standard value assumed; much smaller or much larger maximum sizes provide much lower opacities.

Thus, dust growth is more likely to yield low dust opacities than high dust opacities. Given that some grain evolution probably has occurred, it seems implausible that it always (or at all radii) happened to stop at maximum sizes within an order of magnitude of 1 mm. This view would suggest that T Tauri disk masses have been systematically underestimated. It should also be emphasized that the region of the dead zone at ~ 10 AU may well be optically thick at submm

and mm wavelengths (e.g., Beckwith et al. 1990), so observations of disk dust emission may not be sensitive to the mass in this region.

The typical median dust disk mass estimate is close to the so-called minimum mass solar nebula (MMSN), $\sim 10^{-2} M_\odot$, which is basically sufficient to make Jupiter and little more. However, a significant number of exoplanets have now been discovered which have $M \sin i$ larger than one Jupiter mass, sometimes several Jupiter masses. It is difficult to believe that such systems can be formed without having an initial disk mass considerably larger than the MMSN. While this argument does not by itself require disk masses large enough to be gravitationally unstable, it does suggest that disk mass estimates may be systematically low.

Hartmann et al. (1998) pointed out that accretion rates provide a statistical constraint on T Tauri disk masses. For typical estimates of CTTS accretion rates $\sim 10^{-8} M_\odot \, \mathrm{yr}^{-1}$, lifetimes of 1 - 2 Myr require *minimum* disk masses of $0.01 - 0.02 M_\odot$, a factor of two to four larger than the median mass estimated from dust emission by Andrews & Williams (2005) as discussed above. There are significant uncertainties in estimates of accretion rates, which are mostly derived from ultraviolet and blue-optical continuum excesses, and therefore are sensitive to extinction corrections to accretion luminosities among other problems. On the other hand, it is possible that the accretion rates estimated by Gullbring et al. (1998), Hartmann et al. (1998), and Calvet & Gullbring (1998) have been underestimated systematically by not accounting for red-optical excess emission, perhaps by a factor of two or so (White & Hillenbrand 2004). Increasing the accretion rate estimates systematically would also increase the discrepancy with median dust disk mass estimates.

The solid line in Figure 1 denotes the accretion rate as a function of mass at which 0.1 of the stellar mass would be accreted in 10^6 yr. Accretion rates above this line, if sustained over 1 Myr, would result in accretion of more than $0.1 M_*$ and thus would imply that the disk would have been gravitationally unstable. The steep dependence of accretion rate on mass means that the highest-mass pre-main sequence stars in this diagram – the intermediate-mass ($\sim 1 - 2.5 M_\odot$) classical T Tauri stars (Calvet et al. 2004) – come much closer to this limiting line than the lower-mass objects. Given the obvious point that the accretion to date has not exhausted disk masses, the accretion rate behavior shown in Figure 1 suggests that gravitational instability is a real possibility for at least the higher-mass stars.

Along these lines, it is worth considering accretion in the intermediate-mass stars closer to the main sequence, the Herbig Ae/Be stars. It is not clear that X-ray emission in these stars is sufficient to drive the MRI in their disks. For example, the X-ray emission from one of the nearest and best-studied Herbig Ae stars with an accretion disk, AB Aur, is uncertain. Zinnecker & Prebisch (1994) found that AB Aur was a low-luminosity ($L_X \sim 3 \times 10^{29} \mathrm{ergs}^{-1}$) X-ray source, despite not being detected by EXOSAT or EINSTEIN previously; but Damiani et al. (1994) estimated an upper limit of $L_X < 2 \times 10^{29} \mathrm{ergs}^{-1}$ from the full set of EINSTEIN IPC observations. More generally, by using deep Chandra observations of the very young Orion Nebula Cluster, Stelzer et al. (2005) showed that of 11 mid B- to late-A stars, four were not detected with X-ray luminosity upper limits much

lower than that of the late-type stars in the region, and argued that their results were consistent with a scenario in which the X-rays in the detected objects are is dominated by emission from an unresolved late-type companion star.

Even if Herbig Ae/Be stars do have intrinsic X-ray emission at levels comparable to their lower-mass T Tauri counterparts, higher accretion rates $\sim 10^{-7} M_\odot \, \mathrm{yr}^{-1}$ (Muzerolle et al. 2004) may be difficult to sustain. Interestingly, Grady et al. (1999), Fukagawa et al. (2004), Corder, Eisner, & Sargent (2005), and Pietu et al. (2005) have found evidence for spiral density wave structure in the outer disk of AB Aur. This suggests that either that gravitational instabilities are present, or that the disk being perturbed by a massive object suggesting gravitational fragmentation; either case is consistent with a large outer disk mass, at least initially.

Although gravitational torques can transfer angular momentum outward in disks and thus drive accretion (e.g., Tomley et al. 1991; Laughlin & Bodenheimer 1994; Laughlin et al. 1998), substantial uncertainties remain, including whether the disk fragments or not (Johnson & Gammie 2005). Models have been constructed in which gravitational instabilities resulting from pile-up of material in a dead zone can result in triggering limit-cycle accretion behavior to explain FU Ori outbursts (Armitage, Livio, & Pringle 2001; Book & Hartmann 2005; Book, Gammie, & Hartmann, in preparation). Thus it is not clear that gravitational torques will result in a quasi-steady accretion rate at late evolutionary stages.

The main reason for considering gravitational torques is to limit the sensitivity of accretion in the layered model to dust growth, settling, and overall depletion. To the extent that the MRI-activated layer is not sufficiently thick to be able to pass through accreting material from outer disk regions, low-level gravitational torques could help maintain accretion rates onto the central star.

8. Summary and suggestions for future work

Revisiting Figure 1, one sees that although a dependence of $dM/dt \propto M_*^2$ accounts for the bulk of the data, it also seems that a relation $dM/dt \propto M_*$ might account for the upper envelope of accretion rates. This suggests that objects near the upper limit might be more liable to have layered accretion and dead zones, while the objects (mostly young brown dwarfs) falling well below the upper envelope might have much lower disk masses and thus be fully magnetically active (and have evolved viscously by a substantial amount). In this view it would be misleading to interpret the observations in terms of a universal $dM/dt \propto M_*^2$ relation, as differing processes could be dominant in differing stellar mass regimes.

In general it would not be surprising if the lowest mass stars and brown dwarfs had the lowest mass disks, and thus it seems possible that even modest X-ray emission could make such low mass disks entirely active, increasing the amount of viscous evolution and draining the disk onto the central mass most rapidly to yield low accretion rates at ages of about 1 Myr. More rapid viscous evolution means that the accretion rates of the youngest brown dwarfs must be much higher, by a

significant factor. Thus this model predicts that the decline of mass accretion rates with age should be faster in brown dwarfs than in the nearly solar-mass T Tauri stars (Hartmann et al. 1998). In addition, the brown dwarfs with the very low mass accretion rates should have very low mm-wave emission indicating (roughly) very low-mass disks, although the faintness of the emission will make this prediction difficult to test.

Observations so far indicate no reason why young brown dwarfs accrete in a qualitatively different manner from that characteristic of T Tauri stars. Thus, some of these issues can be explored by studies of very low mass T Tauri stars, which will be brighter and easier to study. The predictions of the previous paragraph can be tested by obtaining much larger samples of mm-wave emission and accretion rate estimates for $0.3 - 0.1 M_{\odot}$ stars. If viscous evolution is faster in lower-mass stars, one should observe a steeper decline of mass accretion rate with age than shown in the higher-mass samples discussed by Hartmann et al. (1998), and mm-wave emission should correlate strongly with accretion rate; the current data are not conclusive on this point, given the limited number of detected brown dwarf disks (Klein et al. 2003; Scholz et al. 2006), the uncertainties in relating this emission to disk mass, and uncertainties in the mass accretion rate determinations.

Layered accretion with dead zones is more likely to occur in higher-mass systems. The existence of dead (or nearly) dead zones is important for planet formation, especially in the 1-10 AU radial range; the higher surface densities are likely to yield faster dust grain growth and settling to the midplane, and the change in the distribution of disk mass as a function of radius could slow down the so-called Type II viscous migration of gap-opening planets (e.g., Lin & Papaloizou 1986). Finally, the possibility of marginally gravitationally-unstable T Tauri disks should not be discounted given the uncertainties in dust opacities, at least for the most massive systems.

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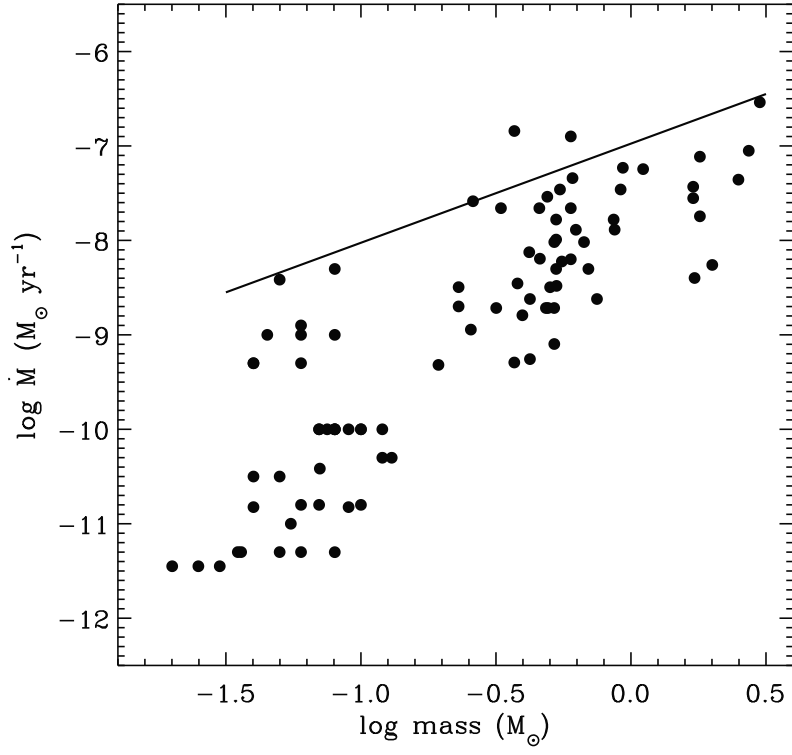
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Fig. 1.— Relation of mass accretion rate and stellar mass, reproduced from Muzerolle et al. (2005), with the addition of a straight line indicating the relation $\dot{M} = 0.1 M_*/10^6$yr. Above this line, sustained accretion for a typical age of 1 Myr would imply an initial disk mass likely to be gravitationally unstable (see text)